ELSEVIER

Energy and Buildings 26 (1997) 23–33

ENERGY AND BUILDINGS

Energy test procedures for appliances

Alan K. Meier [a,*], James E. Hill [b]

[a] Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA
[b] National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

Received 3 December 1995; revised 5 March 1996

Abstract

An energy test procedure is the technical foundation for all energy efficiency standards. It provides manufacturers, regulatory authorities, and consumers a way of consistently evaluating energy use. The ideal test procedure reflects actual usage conditions without compromising reliability and cost-effectiveness. Unfortunately, because these goals are contradictory, every test procedure is a compromise. Energy test procedures exist for a wide range of appliances and often each country has its own unique test procedure. The procedures for refrigerators, furnaces, air conditioners, clothes washers, and other appliances are described and compared. The emergence of microprocessor controls complicates developing specifications for a single operating schedule and simple comparisons of energy performance. Energy test procedures will face unprecedented pressures in the next decade as a consequence of international economic integration and technical innovations.

Keywords: Energy test procedure; Energy efficiency; Standard; Energy use

1. Introduction

An energy test procedure is the technical foundation for all energy efficiency standards, energy labels, and other related programs. It provides manufacturers, regulatory authorities, and consumers a way of consistently evaluating energy use and savings across different appliance models. Test procedures support energy labels, standards, and efficiency programs. A poor energy test procedure can undermine the effectiveness of everything built upon it. The relationship among these components is illustrated in Fig. 1.

Energy test procedures are a poorly-understood aspect of efficiency standards and labels given to appliances. The origins of the test procedures, their validity, and international differences are rarely discussed. As more countries adopt energy efficiency standards, however, test procedures are attracting greater scrutiny. Many appliances (as well as the components within them) are internationally traded or manufactured by multinational corporations having production facilities in different countries. Accordingly, it is now recognized that test procedures may pose a trade barrier. This article describes the overall goals of energy test procedures and follows with discussions of some of the major technical issues involved.

* Corresponding author. Tel: + 1-510-486 4740; fax: + 1-510-486 4673; e-mail: akmeier@lbl.gov

Published by Elsevier Science S.A.
PII S0378-7788(96)01022-5

2. What makes a good test procedure?

An energy test procedure must satisfy several goals. In all cases, an ideal test procedure should:

(i) reflect actual usage conditions;
(ii) yield repeatable, accurate results;
(iii) accurately reflect the relative performance of different design options for a given appliance;
(iv) cover a wide range of models within that category of appliance;
(v) be inexpensive to perform;
(vi) be easy to modify to accommodate new technologies or features; and
(vii) produce results that can be easily compared with results from other test procedures.

Unfortunately, these goals are contradictory. A test that tries to accurately duplicate actual usage will probably be expensive and not easily replicated. For example, the Japanese refrigerator test includes two ambient temperatures (to reflect winter and summer kitchen temperatures) and requires a complex schedule of door openings. These specifications reflect the way a refrigerator is actually used by consumers in their homes, but it is expensive to perform and results are difficult to reproduce. Another example is the United States Department of Energy (USDOE) efficiency test for air conditioners. This test accounts for performance at part-load con-

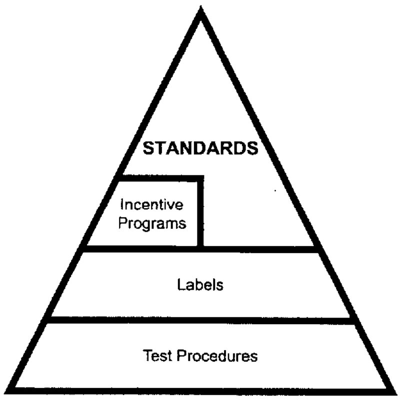

Fig. 1. Energy test procedures represent the technical foundation for all energy efficiency standards and labels. Energy labels cannot be created without an energy test procedure. Standards are, from an enforcement standpoint, impossible without labels. Government or utility incentive programs can be implemented in conjunction with standards or independently, but labels are still necessary.

ditions because the units typically operate a significant fraction of the time at part-load. Again, this understandable attempt to make the test reflect actual operation requires many more measurements and calculations.

The test must yield easily repeatable results. Most ISO energy test procedures for appliances specify a tolerance of 15%. The actual uncertainty is probably much smaller. One study [1] of the USDOE refrigerator test estimated that, if conditions were maintained as prescribed, the measurement uncertainty was less than 2%.

When a test procedure is part of an energy efficiency standard additional considerations are involved. It must be designed such that it is difficult for a manufacturer to circumvent the intent of the test procedure by using technical loopholes. For example, the US washing machine test procedure specifies that energy consumption be measured with the machine on its 'normal' setting. One manufacturer of clothes washers created a 'normal' setting on the machine to satisfy the test procedure but advised consumers to use a more energy-intensive cycle for routine operation.

Clearly, an energy test procedure is a compromise: it does not fully achieve any of the criteria for an ideal test, but it satisfies enough of them to discourage excessive complaints. At a minimum, a ranking of different models by their tested energy use should correspond reasonably close to a ranking by the models' field energy use. An additional danger of compromise is that manufacturers may optimize performance for a test procedure that does not assure energy savings in actual use.

Administratively, all test procedures are difficult to change; as a result, the relative importance of certain objectives may become outdated. In refrigerators, for example, the dominant heat load is conduction through the walls, so current test procedures focus on this. As the walls become better insulated, other factors, such as the energy consumed by automatic defrost, door-opening losses, and ice makers will become more important.

3. Administrative bodies responsible for making test procedures

Test procedures are typically created by such groups as manufacturers' associations, governmental agencies, nongovernmental organizations, and professional societies. A partial list of the major institutions responsible for energy test procedures covering appliances is presented in Table 1. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) rely on an international network of national standards organizations [2]. In Europe, the European Committee for Standardization (CEN) has assumed responsibility for EU-wide test procedures. In the United States, some test procedures were established by the Association of Home Appliance Manufacturers (AHAM) and the Air-Conditioning and Refrigeration Institute (ARI). Technical societies, such as ASHRAE and ASME have also developed test procedures. These associations continue to maintain and update the test procedures, but pressures caused by the adoption of appliance standards, charges of monopoly practices, or international trade negotiations have led to increasing involvement by governments or groups specifically charged with developing standards.

The steps to modify a test procedure are typically cumbersome and time consuming. (Most standards organizations are inherently conservative, so there must be strong pressure before a modification is considered and approved.) These institutions are typically slow in modifying test procedures to adapt to new technologies in the appliances. Now, with appliance standards linked to the test procedures, modifications become more difficult to implement. Many governments also want to review modifications to ensure that they conform to the World Trade Organization requirements in order to prevent the restriction of free trade.

4. Appliances covered by energy test procedures

Almost every energy-consuming device is tested for its rated input and output, voltage, grounding, etc., however, most of these concern safety and electrical service sizing requirements. Most energy test procedures, such as those developed by ISO or the Japan Industrial Standards (JIS), are sections of a much larger document that outlines specifications and test procedures for all aspects related to the performance of an appliance. For refrigerators, specifications include procedures to measure volume, ability to maintain certain temperatures, chill-down capacity, noise, etc.. For washing machines, the list includes cleaning performance, clothes capacity, water removal, noise, etc. Table 2 lists the major appliances covered by energy test procedures. A few countries, such as the United States and Australia, have separate, 'stand-alone', energy test procedures.

The following sections present aspects of energy test procedures for several appliances. The goal is not to describe the test procedures in detail but, rather, to discuss the problems

Table 1
Major institutions concerned with energy test procedures

Institution	Country or region	Address
International Organization for Standardization (ISO)	Global	Case postale 56, CH-1211, Geneva, Switzerland
Association of Home Appliance Manufacturers (AHAM)	USA	AHAM, 20 North Wacker Drive, Chicago, IL 60606 USA
Australia–New Zealand Standard (ANZS)	Australia, New Zealand	Standards Australia, P.O. Box 1055, Strathfield-NSW 2135, Australia
Japan Industrial Standards Committee (JIS)	Japan	Japan Industrial Standards Committee, c/o Standards Department, Ministry of International Trade and Industry, 1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100, Japan
China (CSBTS)	China	China State Bureau of Technical Supervision, 4 Zhi Chun Road, Haidian District, P.O. Box 8010, Beijing 100088, China
Russia (GOST R)	Russia	Committee of the Russian Federation for Standardization, Metrology and Certification, Leninsky Prospekt 9, Moscow 117049, Russia
Korea (KBS)	South Korea	Bureau of Standards, Industrial Advancement Administration, 2 Chungang-dong, Kwachon City, Kyonggi-do 427-010, South Korea
American National Standards Institute (ANSI)	United States	ANSI, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA
Brazil (ABNT)	Brazil	Associaçao Basileira de Normas Técnicas, Av. 13 de Maio, no 13, 27o andar, Caixa Postal 1680, 20003-900-Rio de Janiero-RJ, Brazil
United States Department of Energy (DOE)	USA	Office of Codes and Standards EE-43, Department of Energy, 1000 Independence Ave. S.W., Washington, DC 20585, USA
Deutsches Institut für Normung e.V. (DIN)	Germany	DIN, Burggrafenstrasse 6, D-10787 Berlin, Germany
European Committee for Standardization (CEN)	European Union	Central Secretariat, rue Bréderode 2, B-1000, Brussels, Belgium
Indian Standards Institution (IS)	India	Bureau of Indian Standards, Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002, India
American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)	USA	ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 30329, USA
European Committee for Electrotechnical Standardization (CENELEC)	European Union	rue de Stassart 36, B-1050 Brussels, Belgium
European Committee for Standardization (CEN)	European Union	rue de Stassart 36, B-1050 Brussels, Belgium
International Electrotechnical Commision (IEC)	Global	International Electrotechnical Commission (IEC) PO Box 131, 1211 Geneva 20, Switzerland
Canadian Standards Association (CSA)	Canada	Canadian Standards Association, 178 Rexdale Blvd., Rexdale (Toronto), Ontario M9W 1R3, Canada

commonly encountered in energy tests. Most of the discussions revolve around achieving reasonable compromises among the conflicting goals described earlier.

5. Refrigerators and freezers

Refrigerators and freezers were among the first appliances for which energy test procedures were developed, largely because these appliances use significant amounts of energy and are reasonably easy to test. A list of the major test procedures is given in Table 3.

All of the test procedures involve placing the refrigerator in a controlled environment for a specified time or number of cycles. An excellent overview of the different procedures was published in 1995 by Bansal and Krüger [3]. With the exception of the Japanese procedure, all specify that doors be closed during tests. The principal difference among test procedures is the choice of ambient and compartment temperatures. Even a small difference is significant because small adjustments in temperature settings cause large changes in energy use. Further differences involve dealing with automatic defrost, anti-condensation features, ambient humidity, and food loading. Achieving precise compartment temperatures is difficult: most procedures involve performing the test twice in order to bracket the specified temperature. The energy use for specified compartment temperatures is then obtained through interpolation.

Until recently, the Japanese (JIS) test procedure required energy measurements at two different ambient temperatures (15°C and 30°C). The reason for this is that, at the time the procedure was developed, Japanese kitchens were poorly heated in the winter and not cooled during the summer. The JIS test also includes a door-opening schedule. Japan recently

Table 2
Major appliances with energy test procedures

Air conditioners
Clothes dryers
Clothes washers
Dehumidifiers
Dishwashers
Freezers
Furnaces
Heat exchangers
Heat pumps
Lights
Microwave ovens
Ovens
Refrigerators
Stoves
Swimming pool heaters
Personal computers
Photocopiers
Televisions
Fax machines
Water heaters

abandoned its test procedure in favor of the ISO procedure. As a result, the labeled energy use of Japanese refrigerators suddenly increased by about 40%.

The ISO test procedure is oriented toward European-style refrigerators and their features. It is weaker with respect to specifications regarding automatic defrost, anti-condensation heaters, and special features than the USDOE and Japanese tests. The ISO test can be conducted at two different ambient temperatures depending on the eventual destination of the refrigerator. The temperate zone test uses 25°C, whereas the tropical zone test uses 32°C. European and Japanese manufacturers report the 25°C value because 25°C is specified in the CEN procedure.

The ISO test differentiates refrigerators by their ability to achieve a certain level of performance, which is designated by 1-star to 4-star labeling. To qualify for the four-star rating, the freezer compartment must remain below −18°C. The energy tests reflect this requirement. In contrast, the USDOE test procedure differentiates by technology, that is, whether the model has automatic defrost, partial defrost, or manual defrost. The USDOE energy test does not include performance-based tests.

Technological innovations and new features are constantly being offered in new refrigerators. Even though most innovations are modest, they nonetheless challenge energy test procedures. Some examples are presented below.

Automatic defrosting is present in virtually all Japanese and North American refrigerators. The energy devoted to this task is typically 5 to 15% of total energy consumption. Traditionally, defrosting was activated by a timer, regardless of need. Recently, microprocessor-based controls and sensors have been developed to initiate defrost only when needed. This innovation complicates test procedures because, if no moisture accumulates during the test, no defrost occurs. Should the same defrost schedule be imposed upon all refrigerators, regardless of the controls? The United States' approach to new technologies, such as microprocessor-based logic, is to deduct a fixed amount (or percentage) of energy. This approach treats all sensors and control algorithms as if they perform identically, and thus fails to penalize poorly-designed sensors or control logic.

Some Japanese refrigerators have special compartments for storing fish at exactly −1°C. Other (mostly Japanese) refrigerators have more than four separate doors and compartments. (Several models have six doors.) Should these compartments be maintained at the ISO-required temperatures during the test even though in actual use they will be operated at different temperatures?

An increasing number of refrigerators are equipped with automatic ice makers, chilled water dispensers, and other special features requiring a water connection. These features can increase field energy use by up to 20% [4]. Yet, no tests specify that the water line be connected during the test procedure.

Innovations and features unique to a specific region such as those described above will need to be addressed by the various standard-setting organizations in the next decade.

6. Clothes washers

Clothes washing is a universal activity, and clothes washing machines are used in every country. All test procedures try to account for the energy used by the agitator motor and

Table 3
Major energy test procedures for refrigerators and freezers

Institution	Code number
ANSI/AHAM	ANSI/AHAM HRF-1-1988
ISO	ISO 7371-1985 (and Amendment 1-1987) ISO/DIS 8187.3-1991
ANZS	AS1430 -1986 and NZS 6205.2-1989
JIS	JIS 9607 (1986)
Indian Standard	IS:1476-1979
Chinese Standard	CNS 2062, CNS9577
European Standard	EN 153:1989
United States Department of Energy (USDOE)	Uniform Test Method for Measuring Energy Consumption of Electric Refrigerators and Electric Refrigerator/Freezers, Appendix A1 to Subpart B of Part 430, Volume 10 of US Code of Federal Regulations (10 CFR Ch. II), 1990, (1-1-91 edn.), pp 48–54.

the energy required to heat the water. However, washing habits and the definitions of 'clean' vary enormously from one country to another [5] This situation has hindered the development of international energy test procedures for washing machines. Additional factors, such as variations in the temperature, amount, and hardness (that is, mineral content) of the water, types of detergents, and use of clothes dryers, further complicate defining the energy efficiency of a clothes washer [6]. In addition, given the rapid advances in clothes washing technology, nearly all of the test procedures are being changed. In the United States, for example, there is a current test procedure, a proposed interim test procedure, and a future test procedure. The 'future' test procedure will be put into force only if the efficiency standard for washing machines is approved.

European and American authorities have taken nearly opposite approaches to energy test procedures for washing machines. The US approach defines energy efficiency independently of cleaning performance. The issue of cleaning performance is simply ignored; if a manufacturer fails to deliver satisfactory performance at a given level of energy use, then it is assumed that consumers will purchase a different machine. The European approach is first to define cleaning performance and then, once this definition is available, to select standard requirements that manufacturers must meet to assure both minimum energy use and acceptable cleaning performance.

The United States' approach is already collapsing because of the incorporation of dirt sensors and other controls. In laboratory tests, these sensors recognize that clean clothes are loaded into the washer, so the microprocessor selects the cycle with the minimum energy use. In other words, the test measures the washing machine's energy consumption for the cleaning cycle with the lowest energy consumption.

If the goal of the efficiency standard is to reduce life-cycle energy costs, then detergent should be an important factor in the test procedure, because the detergent itself has a significant energy input and sometimes costs more than the energy used to heat the water. In Europe, detergent represents over 30% of the life cycle cost of clothes washing [7]. Detergent technology is changing, too. Improved chemical formulations have obtained greater cleaning performance at lower water temperatures. At least two test procedures specify a detergent for use in the performance tests. Specifying a 'baseline' detergent may be acceptable for the near future, but will inevitably lead to problems as machines are optimized according to actual detergents available in the market.

Water is a third input to clothes washing that needs to be considered in any good test procedure. Some manufacturers may try to sacrifice water economy for improved energy performance.

In some countries, consumers own both a clothes washer and clothes dryer. (In the USA and the UK, over half of the homes have dryers compared to 20% in Japan and 5% in Portugal) The energy performance of a clothes washer is linked to the clothes dryer. If the clothes washer spins the clothes and extracts most of the water, then only minimal drying is needed from the clothes dryer. Even though the final spin does not affect the cleanliness of the clothes, it does consume energy and, naturally, will affect the machine's apparent efficiency. Thus, a seemingly inefficient clothes washer may be a highly efficient partner when coupled with a dryer. To address this disparity, a proposed USDOE standard will give credit for lower remaining moisture content at the end of the cycle.

A final complication for evaluating the energy efficiency of clothes washers is how the water is heated. The energy invested in heating the wash water is the greatest component of the total energy consumed by the appliance. Most European clothes washers heat the water with an electric resistance heater in the machine itself. In contrast, American and Japanese models rely on heated water from external water heaters. By excluding the energy consumed by the external water heater, the United States and Japanese models will appear more efficient than European models. In addition, many water heaters, especially in the United States, are gas-fired. In terms of test procedures, this introduces the problem of combining the energy contributions from two fuels.

The factors affecting energy test procedures for clothes washers are probably more challenging than for any other appliance. The clothes washer will serve as a bellweather for the international community's ability to reconcile technical, geographical, and cultural differences. If they can be resolved, and an internationally-recognized test procedure approved, then one can expect the same approach to be used with other appliance energy test procedures.

7. Boilers and furnaces

Test procedures for furnaces and boilers prior to the mid-1970s were based on simple steady-state tests where the fuel input and heat output were measured under one set of standard test conditions. For most countries, the steady-state measurement of efficiency remains the sole energy-efficiency test.

Important definitional differences appear even today. German test procedures (DIN) for fossil-fuel-fired furnaces use the 'low' heating values for fuels. In other words, they ignore the latent heat carried away in the combustion products. With the advent of condensing furnaces (which condense the combustion gases and capture the latent heat), reported furnace efficiencies frequently exceeded 100%. In contrast, because North American test procedures are based on the fuel's 'high' heating value, efficiencies never exceed 100%.

The steady-state efficiency test does not necessarily reflect true annual energy consumption because, as with most heating equipment, there is significant energy loss and/or inefficiencies during the start-up and shut-down periods. As a result, the USDOE developed a procedure that includes both steady-state and cycling tests coupled with a calculation procedure that accounts for changing weather conditions throughout the heating season [8].

Although the testing required is simple, the estimation of yearly performance requires an elaborate calculation procedure. The developers found that the performance of furnaces and boilers under part-load, on–off operation could be described by a simple 'time constant' model. In addition, data required to determine the time constant could be obtained after a steady-state test, during 'cool down' and 'warm up', without extensive cycling tests.

Based on extensive laboratory measurements, six loss terms (listed below) were found to be critical to accurately characterizing a furnace's efficiency and are therefore required to be measured:

latent heat loss, from the presence of uncondensed water vapor in the flue gas;

on-period sensible heat loss, from the heating of combustion products and excess air from room temperature up to the flue gas temperature;

on-period infiltration loss, from the heating of relief air during on-cycle combustion and relief air from the outdoor temperature up to room temperature if the air is drawn from a conditioned space;

off-period sensible heat loss, from the heating of the off-cycle draft air up to a temperature in excess of the indoor air temperature;

off-period infiltration loss, from the heating of the off-cycle draft and relief air from the outdoor up to the indoor air temperature if the air is drawn from a conditioned space;

jacket heat loss, to the ambient air if the equipment is not installed in a conditioned space.

These six losses are subtracted from 100 to obtain the value of the seasonal efficiency. To obtain seasonal performance values, the loss terms are evaluated during the heating season using average outdoor air temperatures.

This procedure proved to be as accurate as the more complicated 'bin' analysis where the separate efficiency for calculation for each 'bin' must be separately calculated. In addition, the manufacturer calculates an annual fuel utilization efficiency (AFUE) which differs from the seasonal efficiency if there is consumption of energy by a pilot light operating during the non-heating season.

Since the publication of the original test procedure, the USDOE has modified or proposed modifications to accommodate advances in furnace and boiler technology and changes in control strategy. These advances have included:

(i) Pulse combustion and condensing furnaces [9] where there is very small draft air flow through the heat exchanger during the off-period (pulse combustion) or the latent heat loss is reduced by recovering the latent heat of the water vapor in the flue gas through a condensing heat exchanger (condensing furnace);

(ii) Step-modulating and two-stage controls on furnaces and boilers where furnaces designed with the capability of reduced fuel input rate are cycled between reduced input rate and off when the heating load is light and modulating the input rate up to the maximum input when the load is higher (step-modulating);

(iii) Furnaces with inlet dampers where an electro-mechanical damper at the combustion air inlet of the burner box is automatically closed during the off-period to reduce the draft air flow rate;

(iv) Furnaces with long post-purge time where the combustion blower for power-vented units continue to operate after the burner is shut off, a longer than necessary post-purge time would increase the off-period loss;

(v) Stack dampers with delayed and finite closing time at burner shut-off which will reduce the effectiveness of the dampers in reducing the off-period stack loss.

'Combination heating appliances', that is, products that integrate more than one function into a single piece of equipment or system have become more popular. Typical configurations include a space heating boiler with a tankless water heating coil, a space heating boiler with an indirectly heated domestic water storage tank, or a conventional water heater with additional piping to a heating coil in an air handling unit for forced-air space heating. As indicated, combined appliances pose special problems for testing and comparing with their single-application counterparts.

One industry standard, ANSI/ASHRAE Standard 124-1991 [10], specifies the methods of testing and rating combined heating appliances. The standard specifies that two separate tests are to be conducted. The first is a space heating test that follows the USDOE test procedure for space heating boilers and is designed to obtain a steady-state efficiency and a heating seasonal efficiency for the space heating function; the second is a water heating test that follows the USDOE test procedure for residential water heaters and is designed to obtain an energy factor for the water heating function. The three individual performance parameters (steady-state and seasonal heating efficiencies and energy factor) are used to calculate the rating parameters for the combination appliance by combining them through weighting factors. These weighting factors are based on the fractions of the space heating load and water heating load to the total heating seasonal and total annual space-water heating loads and to the length of the non-heating (space) season to the length of the heating season. Three rating parameters for the combination appliance are calculated: the 'Combined Heating Season Efficiency', the 'Non-heating Season Efficiency', and the 'Combined Annual Efficiency'.

8. Heat pumps and air conditioners

Heat pumps and air conditioners provide different services but operate on the same principle; accordingly, the test procedures are very similar. The fundamental measure of efficiency for these devices is the ratio of heat delivered (or extracted) divided by the electrical input energy. For heating performance, the ratio is called a Coefficient of Performance (COP), and for cooling performance the ratio is called an Energy Efficiency Ratio (EER).

Test procedures to evaluate the performance of air conditioners and heat pumps exist in Europe, Japan, and North America [11–14]. All test procedures measure the appliance's steady-state efficiency, but they differ in the number of additional measurements and calculations required. Test procedures are also specified for outdoor conditions where defrosting of the outdoor coil is periodically required. Similar tests are now included in an ISO procedure [15] which specifies one cooling mode performance test and three heating mode performance tests. For the cooling mode test, however, the prescribed indoor and outdoor ambient conditions (that is, 'cool', 'moderate', or 'hot') depend on the climate conditions present in the eventual destination of the unit.

Whereas the measurements outlined in ISO procedures are sufficient to calculate a unit's steady-state COP or EER, further calculations are needed to estimate seasonal heating or cooling energy consumption. By comparison, North American standards have made estimating seasonal energy consumption the primary goal of its test procedures. In the United States, this goal came about mainly because of energy legislation passed in the mid-1970s that required test procedures to provide an estimate of annual operating cost and/or seasonal efficiency.

As with boilers and furnaces, seasonal performance of air conditioners and heat pumps does not depend only on steady-state performance. The unit's performance during the transient periods at the beginning and end of an on-cycle and the parasitic electrical energy used during an off-cycle also affect seasonal performance. From its inception, therefore, the USDOE test procedure for air conditioners and heat pumps has included a cooling mode cyclic test and a heating mode cyclic test [16,17]. For single-speed and two-speed capacity units, a cycle consisting of a 6 min on-period followed by a 24 min off-period is repeated a few times before data for one complete on–off interval are collected. A measure of the degradation associated with cyclic operation is gained by using the results of these cyclic tests plus the results from the steady-state tests conducted under the same test conditions. The tandem cyclic and steady-state (dry coil) cooling mode tests and the one cyclic heating mode test are optional. Default values for the cyclic degradation are provided in the test procedure.

Using data from steady-state tests conducted at outdoor temperatures of 35°C and 27.8°C plus the cyclic degradation coefficient, an estimate can be determined of the seasonal performance descriptor for the cooling season, Seasonal Energy Efficiency Ratio (SEER)[1]. Initially, for all air conditioners and heat pumps, the SEER calculation procedure used the bin method mentioned in Section 7 where performance is weighted by the number of hours the unit operates in each outdoor temperature range or bin. In contrast to the AFUE of furnaces and boilers, however, the SEER for single speed air conditioners and heat pumps was found to vary minimally for climate conditions typically found within the continental United States. A very close approximation of the bin-determined SEER was obtained by using only the results from testing conducted at 27.8°C.

On the heating side, the Heating Season Performance Factor (HSPF) is calculated using a bin method. The effects of frosting are assumed to occur over an outdoor temperature range of −8.3 to 7.2°C for single-speed and two-speed models when they are operating at high capacity. The HSPF of a heat pump varies with climate. Moreover, within a given climatic region, the heat pump, theoretically, could be applied to homes having very different design building loads. As a result, the USDOE test procedure contains information allowing the HSPF to be evaluated for six different climate regions and for a range of design building loads within each region. For rating purposes, however, the HSPF corresponding to a single climate region is reported.

Since the initial publication, the USDOE test procedure has been modified to cover split-type ductless systems and variable-speed systems [18]. Also, calculation procedures have been developed for rating mixed systems, that is, where an indoor and outdoor unit have not been tested as a system [19,20].

United States manufacturers of complete systems are required to test each type of outdoor unit with one indoor unit. The indoor coil is the one that is most frequently sold with the particular outdoor unit. All other combinations of indoor and outdoor units are not required to be tested. In lieu of testing, a manufacturer (including those that manufacture only indoor coils) uses a USDOE-approved method for predicting rated cooling capacity, SEER (and, for heat pumps, rated heat capacity and HSPF). Manufacturers have the option of submitting their own method or using the methods developed by USDOE. Often, manufacturers use the USDOE methods but then incorporate their own company-specific changes. These rating methods are structured such that the performance of the mixed system is ultimately derived on the basis of performance of the indoor/outdoor combination that was tested, which is termed the 'matched' system.

Combined appliances are also appearing with heat pumps and air conditioners. The most common combination is an air conditioner/domestic water heater. Heat extracted from the refrigeration system is used to heat the water in the storage tank, thus reducing the amount of heating the water heater must do. When operating in the space cooling mode, for example, all or a portion of the heat that would normally be rejected to the outdoor air is instead productively used for heating potable water. These types of combined appliances come in two basic categories: full condensing units and units that incorporate desuperheaters. The main difference between the two is that full condensing units can provide on-demand water heating by operating in a combined mode and in a water-heating only (dedicated) mode. Units having a desuperheater only provide hot water when the unit operates to condition the space.

[1] Note that SEER is expressed in customary US units, that is, Btu/h. A seasonal COP can be obtained by dividing by 3.412.

ASHRAE has recently completed work on a standard method for testing single-speed, air-source air conditioners and heat pumps that incorporate a desuperheater [21]. The Air-Conditioning and Refrigeration Institute (ARI) is developing a standard method for rating both categories of combined appliances [11]. The USDOE has approved a method for testing and rating air-source full-condensing units built by two manufacturers.

9. Declared energy use versus test procedure values

The previous discussion refers to measuring the energy consumption of a single appliance using the required test procedure. A test procedure is insufficient, however, if the goal is to demonstrate compliance with a minimum energy efficiency standard or to provide a labeled energy use for that appliance. Fluctuations in manufacturing and testing mean that the test value for a single unit will probably not be representative of the thousands being produced. For this reason, most regulatory authorities have established procedures to test the minimum number of units to ensure a certain level of statistical confidence. The sampling procedure links the test procedure to the labeled value and compliance with the standard. Three sampling procedures, from the United States, the European Union, and Canada will be summarized. All three procedures rely on a 'declared value' of energy consumption that satisfies the confidence requirements. The general approach is the same for each appliance but confidence requirements depend on the appliance.

The European test procedures, such as the one for refrigerators and freezers (EN-153) [22] require the manufacturer to test the energy consumption for one appliance. The declared value is the tested value plus 15%. Alternatively, the manufacturer can test three units and declare a value equal to the arithmetic mean. This second option gives manufacturers with a high degree of quality control an opportunity to declare a few percent lower energy use for their models.

The Canadian standards, such as that for electric clothes dryers [23], specify that the declared value must be based on a sample of units. The sample size is not specified because the manufacturer has two options, either taking the simple mean of the sample as the declared (or 'represented') value or demonstrating (with a 97.5% confidence) that the declared value is 1.05 times greater than the true mean. Again, manufacturers with a high degree of quality control can achieve a slightly lower declared energy consumption because less scatter will narrow the confidence limits. Most standards (e.g., those for clothes dryers, refrigerators, etc.) are expressed in terms of maximum allowable energy consumption but some (those for furnaces and air conditioners) are expressed in terms of minimum efficiency. In these cases, the adjustment factor (away from the mean) is 0.95, and the confidence limit is in the other direction.

The sampling requirements for the United States standards [24] are essentially the same as for the Canadian standards. For both countries, the confidence limits and the adjustment factors vary with the appliance. The confidence limits range from 90% to 99%. The adjustment factors vary from 1.01 to 1.10 for products for which the consumer will benefit from a lower value and 0.90 to 0.99 for products for which the consumer will benefit from a higher value. The number of tests needed to meet these criteria will obviously vary. In the case of refrigerators, however, typically 4–6 units must be tested [25].

Efficiency standards can affect the declared values in other, less predictable ways. Many refrigerators have electric resistance heaters around the perimeters of the doors to reduce condensation. Because these heaters can increase a refrigerator's energy use by up to 15%, some manufacturers install a switch to turn off the option when the heaters are not needed. Other manufacturers, however, wire the heaters to be permanently switched on. Should the energy tests for those units with switches be conducted with the switch on or off? The initial regulatory compromise required the manufacturers to use the average energy use in the on and off settings. Later, the USDOE modified the rules requiring manufacturers to calculate the average of a test with the heater switched on and another test with the heater switched as shipped from the factory. Thus, the declared energy use of many refrigerators simply depended on the manufacturers' decision regarding the heater setting when packaging and shipping the refrigerators. These kinds of rules greatly complicate assigning and understanding the declared values.

10. Translating results from one test procedure to another

Energy tests, whether for standards or labels, are expensive. An internationally recognized testing laboratory charges roughly US$ 2000 to perform the USDOE test procedure on a single refrigerator and US$ 6000 for a central air-conditioning unit [25]. The laboratory tests and administrative work needed to create a European Union energy label for a clothes-washing machine cost about US$ 3800 [26]. Accordingly, international manufacturers of appliances would like to convert results from one test to the values of another.

In spite of the recognized need for conversion formulas, surprisingly few attempts to develop conversion formulas have been undertaken. Given the limited published research available, conversion formulas appear to give only approximate values for other test conditions. While these conversions will be useful for approximate comparisons, they will never be reliable enough to satisfy regulators.

Almost all comparisons that have been done deal with refrigerators, the most extensive study of which was conducted by Bansal and Krüger [3]. They tested four refrigerators using the ISO, Japanese, US, Australian–New Zealand, and Chinese test procedures. Each refrigerator exhibited unexpectedly different relationships among the test procedures. For example, the ISO test of the four units was 2–64% less than the United States test values. The conversion from the Japanese to the ISO standard was not even consistent in one direction: the ISO values ranged from 0.87–1.33 times the Japanese values. This range may also reflect the diversity among the units tested. As indicated previously, Japan switched from the JIS to the ISO test procedure in 1995. During 1994–95, both values were listed in the manufacturers' catalogs, and the ISO values were consistently 35–45% higher than the JIS values for automatic defrost refrigerator/freezers. In an earlier comparison of the JIS and USDOE test, Meier [27] found that the ratio varied with the unit's size and features. Models with similar capacities and features had reasonably similar (within about 10%) ratios of JIS/USDOE test values or conformed to a simple linear translation [28].

Conversion of air conditioner EERs from one test to another should, in principle, be simpler because there are fewer variables in the test procedure. However, the US has diverged from most of the world by developing 'seasonal' EERs for central air conditioners and heat pumps. These SEERs rely on performance data of the individual machine at three pairs of indoor and outdoor temperatures, as well as local climate data. Even though there is no straightforward conversion from DOE to ISO values, it is possible to make reasonably accurate conversions if the input data to the DOE value are available. (The steady-state efficiency is one of the measurements made.) There is also confusion within the ISO test procedure itself because it allows testing at any one of three ambient temperatures. If one manufacturer chooses to test at the lower temperature and another manufacturer at the higher temperature, then comparisons are impossible. In addition, manufacturers often fail to clearly note which temperature they used.

Measurements of efficiencies of fuel (oil, gas, and kerosene) appliances are generally straightforward, and so is conversion from one procedure to another. However, none of the tests include the electricity consumed by associated fans and pumps. As mentioned before, the electricity consumption of these components is often significant. Unfortunately, however, there is no agreement on how to combine the fuel and electrical energy, that is, should the site electricity be converted to primary energy to reflect generation and transmission losses? If purely site energy is considered (e.g., 1 kWh equals 3.6 MJ), then the higher cost of the electrical energy, in addition to the conversion losses, is not reflected in the efficiency values.

As international trade in appliances grows, there will be increasing pressure for a single, global energy test procedure for each appliance. In fact, harmonized tests already exist for many electronic appliances, such as televisions and photocopy machines, because these appliances have been internationally traded almost from their inception. Additional efforts toward harmonization are discussed by Turiel [29] and Nadel [30]. Progress is slower where regional differences have evolved in the services provided by the appliances (such as refrigerators, washing machines, and air conditioners).

There are obvious trade benefits to harmonized test procedures. Indeed, since most refrigerators are now produced by large, multi-national corporations, it is difficult to understand why local variations remain. However, there are also drawbacks to harmonized energy test procedures. A single procedure cannot address unique local conditions or cultural preferences. For example, Japan and the United States, countries where hot, humid weather conditions are common, are much more concerned than the European Union is about an air conditioner's ability to remove latent heat. One possible solution is to develop a harmonized basic test procedure and supplement it with nation-specific variants. For example, the United States might require an additional energy test for the air conditioner at part load, and Japan might want a humid conditions test. Although this approach is attractive on the surface, it still fails to accomplish the goal of one energy test for all countries.

11. The impact of microprocessors on energy test procedures

Few test procedures adequately address the benefits of microprocessor-based controls and some actually penalize manufacturers of appliances that have them. Appliances with microprocessors can exploit special sensors, fuzzy logic, variable speed, and other innovations to provide near-infinite adjustments to appliance operation in response to the specific conditions encountered or desired by the consumer [31]. Combinations of sensors and 'intelligent' controls were originally applied to simple functions, such as the defrost cycles in refrigerators, but their use quickly expanded to complex controls for air conditioners, dishwashers, and washing machines.

Microprocessors are integral elements of many pure electronic appliances, such as fax machines, computers, and copiers. Traditional appliances controlled by microprocessors obviously provide additional convenience to consumers, but they often save energy as well. These controls save energy by, for example, initiating defrost cycles in refrigerators and heat pumps only when required, preventing overfilling of washing machines with hot water, and improving part-load efficiency of air conditioners.

As useful as this technology has been to consumers, it is much more difficult to devise or modify an energy test procedure when the appliance is specifically designed to intelligently conserve energy. The use of microprocessors in appliances complicates the development of test procedures by:

(i) saving energy in situations not covered by a test procedure;

(ii) responding automatically to laboratory conditions that cause an unrealistically low observed energy use;

(iii) modifying operations by 'learning' from user behavior;

(iv) consuming electricity while 'off'; and

(v) increasing electricity use in situations not covered by a test procedure.

In other words, the microprocessor, by yielding an unrealistically low test value or achieving superior field performance to that predicted by the test procedure, can undermine the value of the test procedure.

For example, a microprocessor, combined with a variable speed motor, allows an appliance to adjust its output to the load, which reduces off-cycle losses and improves efficiency. The benefits of variable capacity do not appear in steady-state tests but can lead to significant field energy savings for air conditioners and heat pumps.

An intelligent appliance can frustrate a test procedure by recognizing that it is not performing in a realistic situation. Dirt sensors in washing machines represent a good example. Recognizing that the test clothes are clean, the washing machine selects an energy-saving cycle rather than the normal cycle. Even modern refrigerators can frustrate the test procedure. The microprocessor's role in controlling the timing of defrost in refrigerators has already been discussed.

Most older electromechanical appliances were truly 'off' when not operating. This is not the case for new appliances having electronic components that require a constant supply of low voltage electricity. The low voltage transformer and the microprocessor create a low level, constant electricity 'leak' [32–34]. For new, efficient refrigerators, the consumption of electronics represents 5% of total consumption [33] while ductless air conditioners typically draw over 10 W [35]. Again, the constant consumption of electricity is generally not included in the calculation of an appliance's energy use.

The presence of microprocessors in variable-speed air conditioners and heat pumps may lead to worse performance than indicated by test procedures. The EER is measured at the rated capacity; however, variable-speed units can be operated at significantly above rated capacity. Efficiency drops rapidly above rated capacity. Certain usage patterns can make this a serious problem for utilities. In Japan, for example, variable-speed air conditioners were promoted for their energy efficiency. Unfortunately, their efficiency during peak cooling periods was actually worse than the single-speed units that they replaced, and this led to even sharper peaks in electricity demand.

Almost all energy test procedures will need to undergo major revisions in the next decade to accommodate the presence of microprocessor control. In the short run, simple credits or adjustments to the tested values can be applied to appliances having certain features. For example, the manufacturer may reduce the tested value for a dishwasher if the unit has a dirt sensor. Unfortunately, this strategy does not distinguish between well-designed and poorly-designed controls. In the long run, the only solution is to develop performance-based test procedures.

12. Conclusions

Energy test procedures represent the technical foundation for all energy efficiency standards and labels. Test procedures provide a means for manufacturers, regulatory authorities, and consumers to compare the energy consumption of different models of appliances in a consistent manner. Given the diverse range of users, it is no surprise that test procedures are compromises between representing realistic usage patterns and performing measurements that are reliable and cost-effective. The direction of the compromise varies with the appliance; for example, the test appears to favor realistic usage patterns for clothes washers while favoring economy for air conditioners. This balance will certainly change as the relative influence of each stakeholder changes, but the results of energy tests will still play an important role in many private, commercial, and public policy decisions.

Energy test procedures will face unusual pressures in the next decade as a consequence of administrative and technical developments. As countries work to establish energy efficiency standards, the details of every test procedure will come under more scrutiny. Manufacturers will seek to make the testing requirements simple and inexpensive. Foreign manufacturers will regard complex or unique test procedures as a trade barrier. In addition, domestic manufacturers will want to ensure that their products appear as energy efficient as possible, while consumers will want the test procedures to reflect as realistic results as possible. Meanwhile, continuing technological innovations will undermine the ability of existing procedures to reasonably represent an appliance's energy efficiency. The incorporation of microprocessors in appliances means that future test procedures will need to measure the performance of an appliance's mechanical features *and* the software that controls it. Finally, new features appearing in appliances—from automatic ice making in refrigerators to dehumidification modes in air conditioners—will cause consumers to use appliances differently, thereby rendering the test procedures obsolete.

Test procedures of all types are generally regarded as obscure, dry, and highly technical. The issues are indeed complex, but there are also technical, economic, cultural, and behavioral aspects tugging in every direction at once. They are important because small differences in the details of the test procedures can have a large impact on energy use, the environment, and the international economy. There are no simple solutions to these challenges, but understanding the complexities involved is fundamental to devising a framework for tackling them.

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy of the US Department of Energy under Contract No. DE-AC03-76SF00098. The authors thank Brian Dougherty, Stan Liu, and Jim Kao of the National Institute of Standards and Technology, Peter Biermayer and Gregory Rosenquist at Berkeley Lab, and Don Mackay of the Air-Conditioning and Refrigeration Institute for their assistance in the preparation of this paper.

References

[1] K.J. Farley, M.S. Alissi, S. Ramadhyani and R.J. Schoenhals, Effects of ambient temperature and control settings on thermal performance and energy consumption of a household refrigerator/freezer, *ASHRAE Trans., 93* (1987) 1578.

[2] ISO, Introduction to ISO, *Rep. No. http://www.iso.ch/infoe/intro.html,* International Organization for Standardization, Geneva, Switzerland, 1996.

[3] P.K. Bansal and R. Krüger, Test standards for household refrigerators and freezers. I: Preliminary comparisons, *Int. J. Refrig., 18* (1995) 4.

[4] A. Meier and M. Martinez, Energy use of ice making in domestic refrigerators, *ASHRAE Trans., 102* (1996) 1071.

[5] H. Couvreur, J. Gouda and M. Scott, Fabric washing in Western Europe, *37th Int. Detergency Conf. Krefeld, Germany,* Forschungsinstitut für Reinigungstechnologie e.V., Krefeld, Germany, 1996, pp.15–18.

[6] Group for Efficient Appliances, Washing Machines, Driers and Dishwashers, *Rep. No. ISBN: 87-7844-014-9,* Danish Energy Agency, Copenhagen, Denmark, 1995.

[7] R. Kemna, Long-term efficiency targets for the residential washing machine: design options and life-cycle analysis for Europe, *37th Int. Detergency Conf. Krefeld, Germany,* Forschungsinstitut für Reinigungstechnologie e.V., Krefeld, Germany, 1996, pp. 22–27.

[8] G.E. Kelly, J. Chi and M.E. Kuklewicz, Recommended testing and calculation procedures for determining the seasonal performance of residential central furnaces and boilers, *Rep. No. NBSIR 78-1543,* National Bureau of Standards, Gaithersburg, MD, October, 1978.

[9] G.E. Kelly and M.E. Kuklewicz, Recommended testing and calculation procedures for estimating the seasonal performance of residential condensing furnaces and boilers, *Rep. No. NBSIR 80-2110,* National Bureau of Standards, Gaithersburg, MD, April, 1981.

[10] ANSI/ASHRAE, Methods of testing for rating combination space-heating and water-heating appliances, *ANSI/ASHRAE Standard 124-1991,* American National Standards Institute, New York, 1991.

[11] Air-Conditioning and Refrigeration Institute, Unitary air- conditioning and air source heat pump equipment standard, *Rep. No. 210/240-89,* Air-Conditioning and Refrigeration Institute, Arlington, VA, 1989.

[12] Performance standard for single package central air conditioners and heat pumps, *Rep. No. CSA-C656-M92,* Canadian Standards Association, Toronto, 1992.

[13] European Standard, air/air heat pump units, *European Union Rep. No. CEN-255,* European Committee for Standardization (CEN), Brussels, Belgium, 1988.

[14] Japan Industrial Standards Committee, Testing methods for unitary air conditioners, *Rep. No. JIS B 8615-1984,* Japan Industrial Standards Committee, Tokyo, 1984.

[15] ISO Standard, Ducted air conditioners and air-to-air pumps—testing and rating for performance, *Rep. No. 13253,* International Organization for Standardization, Geneva, Switzerland, 1996.

[16] G.E. Kelly and W.H. Parken, Method of testing, rating, and estimating the seasonal performance of central air conditioners and heat pumps operating in the cooling mode, *Rep. No. NBSIR 77-1271,* National Bureau of Standards, Gaithersburg, MD, April, 1978.

[17] W.H. Parken, G.E. Kelly and D.A. Didion, Method of testing, rating, and estimating the heating seasonal performance of heat pumps, *Rep. No. NBSIR 80-2002,* National Bureau of Standards, Gaithersburg, MD, April, 1980.

[18] P.A. Domanski, Recommended procedure for rating and testing of variable speed air source unitary air conditioner and heat pumps, *Rep. No. NISTIR 88-3781,* National Institute of Standards and Technology, Gaithersburg, MD, May, 1988.

[19] P.A. Domanski, Rating procedure for mixed air source unitary air conditioners and heat pumps operating in the cooling mode—Revision 1, *Rep. No. NISTIR 89-4071,* National Institute of Standards and Technology, Gaithersburg, MD, July, 1989.

[20] P.A. Domanski, Rating procedure for mixed air source unitary heat pumps operating in the heating mode, *Rep. No. NISTIR 90-4298,* National Institute of Standards and Technology, Gaithersburg, MD, May, 1990.

[21] ASHRAE, Methods of testing for efficiency of space-conditioning/water-heating appliances that include a desuperheater water heater, *Rep. No. 137-1995,* American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 1995.

[22] European Committee for Standardization, Methods of measuring the energy consumption of electric mains operated household refrigerators, refrigerator/freezers, frozen food storage cabinets, food freezers, and their combinations, together with associated characteristics, *Rep. No. EN 153,* European Committee for Standardization, Brussels, Belgium, March, 1989.

[23] Canadian Standards Association, Test method for measuring energy consumption and drum volume of electrically-heated household tumble-type clothes dryers, *Rep. No. CAN/CSA-C361-92,* Canadian Standards Association, Toronto, November, 1992.

[24] US Department of Energy, Uniform test method for measuring energy consumption of electric refrigerators and electric refrigerator/freezers, *Code of Federal Regulations, Appendix A1 to Subpart B of Part 430.23 (10 CFR Chap. II),* Government Printing Office, Washington, D.C., 1994.

[25] United States General Accounting Office, Energy conservation appliance standards and labeling programs can be improved, *Rep. No. GAO/RCED-93-102,* United States General Accounting Office, Washington, DC, March, 1993.

[26] U. Sommer, Energie-Label für Waschmachinen Kriterien-Prüfmethode-Toleranzen, *37th Int. Detergency Conf., Krefeld, Germany,* Forschungsinstitut für Reinigungstechnologie e.V., Krefeld, Germany, 1996, pp. 28–38.

[27] A.K. Meier, Energy use test procedures for appliances: a case study of Japanese refrigerators, *ASHRAE Trans., 93* (1987) 1570.

[28] A. Meier, Refrigerator energy use in the laboratory and the field, *Energy Build., 22* (1995) 233.

[29] I. Turiel, Status of appliance labels and efficiency standards: an international review, *Energy Build., 26* (1997) 5.

[30] S. Nadel, The future of standards, *Energy Build., 26* (1997) 119.

[31] H.G. Hloch, Tendenzen im Bereich Wasch- und Spülmaschinen, *37th Int. Detergency Conf., Krefeld, Germany,* Forschungsinstitut für Reinigungstechnologie e.V., Krefeld, Germany, 1996, pp. 8–14.

[32] E. Sandberg, Electronic home equipment-leaking electricity, *The Energy Efficiency Challenge for Europe,* Vol. 1, European Council for an Energy-Efficient Economy, Rungstedgard, Denmark, 1993, pp. 373–375.

[33] L. Rainer, A. Meier and S. Greenberg, Leaking electricity in homes, *ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA,* American Council for an Energy-Efficient Economy, Washington, DC, 1996.

[34] R. Perez, Phantom loads, *Home Power,* October/November, (1993) 46.

[35] H. Nakagami, Jyukankyo Research Institute, Personal communication, March 13, 1996.